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## Karst Terrane and Transportation Issues

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### Glossary

**Carbonate rocks** Bedrock that is composed of calcium carbonate, such as sedimentary rocks like limestone and dolostone.

**Cave** A natural cavity or series of galleries that is produced by solution of limestone and is large enough to be entered by man.

**Centerline** A term that refers to the center of a road or highway and runs the length of the road or highway.

**Collapse** A term used in conjunction with the formation of sinkholes; the subsidence of land or bedrock due to an underlying cavity.

**Ditchline** A term used in roadway design and construction that refers to a drainage ditch that is parallel to the roadway and located on either side of the road, and sometimes in the median of the road.

**Gabion basket** A basket configuration constructed from double-twist wire meshing; typically the basket is backfilled with rock or gravel to form a semirigid retaining wall.

**Geomembrane** Typically a synthetic man-made material that is usually impervious to water penetration; e.g., is a swimming pool liner; used in roadway construction to reinforce embankments and line ditches.

**Groundwater** That part of the subsurface water which is in the zone of saturation; also called phreatic water.

**Grout** A term that refers to thin fluid mortar; commonly used in construction and often used to fill in cavities in limestone to produce a stable foundation for a road, bridge footing, or dam.

**Karst** A landscape underlain by carbonate rocks, such as limestone and dolostone, that exhibit such features as sinkholes, sinking streams, caves, and subsurface drainage; e.g., central Kentucky Mammoth Cave region.

**Lined ditch** A term used in highway design and construction that refers to a drainage ditch that has an engineered “bottom” such as concrete, asphalt, or geomembrane.

**Ponor** A karst feature where a surface stream disappears into the subsurface, usually via a sinkhole or cave entrance.

**Recharge** A term that usually refers to the replenishing of a substance, usually used in association with the groundwater table; i.e., recharging the groundwater.

**Regolith** The layer or mantle of loose weathered rock and soil debris that forms the surface of the land and rests upon hard bedrock material; most commonly associated with the soil horizons overlying bedrock.

**Reinforced concrete** Concrete that is strengthened by using steel bars.

**Roadway alignment** The general configuration and direction of a roadway.

**Rock pad** A term used in construction that refers to a layer of quarried and/or crushed rock that is used to form a hard stable layer or foundation, and also provides for drainage of water seeps.

**Sinkhole** A circular or funnel-shaped depression in the landscape of a limestone region usually formed by the solution of limestone and the subsurface erosion of the overlying regolith; can occur rapidly and catastrophically causing great damage to roads and structures.

**Solution** Typically the change from a solid, such as limestone into the liquid state by its combination with a liquid; usually associated with karst.

## Definition of the Subject

As roads, highways, bridges, and railroad corridors are built to better transport our society, the terrane that they are located in may dictate design and construction procedures necessary to produce a stable and safe transportation route. One such terrane is karst, a landscape that is typically underlain by carbonate rocks such as limestone and weathers chemically and physically to produce features such as sinkholes and caves.

Designing, constructing, and maintaining these transportation systems that are located in karst terrane require proactive techniques to better stabilize the road or bridge. Too often a reactive approach to dealing with karst issues is pursued by transportation agencies. Being more proactive toward karst issues can lessen maintenance costs and also protect the environment.

## Introduction

Dissolution of bedrock in areas underlain by carbonate rocks (usually limestone or dolomite) results in a terrane characterized by sinkholes, sinking streams, underground (cave) streams, and springs. (The entire landscape formed in soluble rock areas is known as a karst terrane. The term *terrane* is used rather than *terrain* to include subsurface features as well as surface features.) This terrane is usually referred to as karst. Groundwater in these settings is more susceptible to contamination because surface water may pass directly into the subsurface with little or no filtration by soil.

Because karst groundwater typically flows through relatively large fractures and conduits within the bedrock, it may transport contaminants rapidly from points of recharge (such as sinkholes) to distant cave streams, water wells, springs, and surface streams.

A karst landscape can be composed of gently rolling hills and valleys textured with sinkholes, cave entrances, sinking streams, and outcroppings of weathered limestone (Fig. 1) as is typically found in Kentucky and Tennessee and the Virginia/West Virginia/Pennsylvania sections of karst. Dramatic topography that exhibits tall “haystack”-type karst terrane as found in the Li River section of southwest China (Fig. 2) can be impressive and a daunting landscape for highway construction.

Existing roads in karst areas usually experience the sudden collapse of a sinkhole or the flooding of a sinkhole basin crossed by a road. In addition, issues of groundwater pollution often go unchecked or not addressed by highway agencies as well as developers and city planners.

To the geologist and geotechnical engineer, caves are more than just curious features because they reveal information about the groundwater movement and solution processes that act on carbonate rocks. The patterns in which the solution cavities and resulting caves develop generally indicate the attitude of the bedrock, fracture density, and groundwater movement. Cave passage patterns, sinkholes, and springs are important features that may contribute to an understanding of the local groundwater flow. The recognition of areas of active karst subsidence and collapse is of considerable importance to those engaged in the design and implementation of highways, especially the construction of infrastructure.

Some of the problems that have resulted from human modification of karst into subdivisions, highways, and commercial properties include the subsidence of building foundations and the collapse of lawns due to leaking swimming pools, and inappropriately located septic tanks (Fig. 3). The collapse of highway surfaces (Fig. 4), ditch lines, and bridge foundations, as well as numerous instances of flooding are also karst-related problems triggered by human construction activity. In most instances, it is the impact of human construction activity and alteration to the surface drainage that induces the collapse of a highway



**Karst Terrane and Transportation Issues. Figure 1**

Features such as sinkholes and cave entrances such as this Roane County, Tennessee cave entrance, often characterize karst terrane

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**Karst Terrane and Transportation Issues. Figure 2**

A karst region in China is characterized by remarkable landscape relief as shown here along the Li River near Guilin, China



or house foundation or results in the flooding of a commercial strip mall.

Solution cavities developed in karst terrane characteristically have numerous open subsurface flow paths. Accordingly, any contaminating fluids are able to be rapidly dispersed along difficult-to-predict routes. This type of groundwater contamination from highway runoff is becoming a greater concern as transportation routes are expanded into karst areas.



**Karst Terrane and Transportation Issues. Figure 3**  
Sinkholes can occur most anywhere in karst areas, as evidenced by this sinkhole near Morristown, Tennessee

This is particularly so in karst areas where toxic or hazardous spills along highways can directly flow from the highway into sinkholes and cave systems that recharge groundwater aquifers. Everyday highway runoff including tar, gasoline, diesel fuel, asbestos, and metals from the roadway can also contaminate groundwater supplies where the runoff flows into sinkholes affecting the groundwater quality.

Most of the remedial activity concerning karst problems has been reactive in nature. In most instances it is highway maintenance personnel that tend to remediate these sinkhole collapse and runoff problems. The reactive approach to dealing with karst problems involves responding in an emergency situation.

Remedial action is usually adopted in response to karst problems. Remedial concepts used for correcting karst problems include bridging, drainage, and relocation measures. Bridging a collapse with a rock fill or a concrete structure may be one alternative. Trying to solve flooding problems may require the use of existing sinkholes for drainage outlets (possibly resulting in groundwater contamination) or even constructing special ditches to bypass sinkhole areas to access a nearby stream. Sometimes moving a section of road or relocating a house is the course of action required.



**Karst Terrane and Transportation Issues. Figure 4**  
Karst terrane can impact our highways as shown in this photo of a sinkhole along I-40 near Knoxville, Tennessee

If proper consideration is given to karst problems in advance of a construction project, then proactive measures can be taken that involve the understanding of karst processes. By simply avoiding a karst area when planning a highway or developing a commercial zone or residential subdivision, one can save future agony as well as dollars for the home owner, developer, or government agency. If avoidance is not possible, then there must be certain integrated measures taken that address not only potential subsidence but also flooding and groundwater contamination.

In general, transportation issues in karst terrane deal mostly with sinkhole collapse problems, sinkhole flooding, groundwater pollution, and environmental issues dealing with caves and cave inhabitants. How these issues are dealt with usually falls into reactive measures and proactive measures.

### The Character of Karst

As would be expected the character of karst can be varied and unusual, and is often dramatic. Caves and sinkhole collapse are the most common karst characters and are often the features encountered when designing and constructing highways. Sinkhole plains, disappearing streams, resurging streams, subsurface drainage, and delicate ecosystems are also characteristic of karst and presents tenuous issues when locating or constructing transportation infrastructure.

The geologic character of the bedrock also plays an important role in the development of karst features. In addition to lithology, structural characteristics such as fracture density, folding, and faulting also contribute to the development of karst. Long linear belts of karst tend to develop on folded and faulted strata whereas flat-lying strata tend to develop wider, dendritic-type expanses of karst. In addition, highly fractured strata provide more avenues for solution activity of groundwater and therefore develop into a karst landscape quicker than less fractured strata. There are numerous studies that describe the relationship between geologic structure and karst development such as [4, 14, 31, 32, 38, 51, 52].

Cave development in karst areas, like those in the East Tennessee region, central Kentucky, and other karst areas around the USA, follows the more soluble zones or lines of weakness within the host bedrock.

These weak areas are generally parallel to zones of fractures (joints and faults) or bedding planes of the rock. Solution enlargement of these weak areas of fractured rock generally coalesce into interconnecting passages that form intricate caverns, some of which are profusely decorated with cave formations (speleothems or dripstone) [26, 29].

Surface expression of the subsurface conditions in karst areas is usually manifested as depressions and sinkholes (Fig. 5). The sinkholes vary in size from several feet to several hundred feet across and up to tens of feet in depth. Some of the sinkholes may have active swallets or openings into the cave environments, while others may be simply silted in and covered with vegetation. Additionally, numerous rock outcrops are present, as well as sinking streams, cave entrances, and springs. Most all of these conditions are present along highways in the karst areas of the USA.

Sinkhole development along highways usually results from the collapse of the residual clay soil into cavities developed in the subsurface soil due to erosion of the residual clay. As these “soil cavities” enlarge and approach the surface, the remaining soil bridge over the cavity loses strength and collapses forming a typical sinkhole collapse. The eroded soil is flushed down into the solution cavities in the bedrock. This type of induced sinkhole failure has been previously described by Donaldson [9], Jennings, et al. [15], Moore [22, 24], and Newton [34, 35].

The majority of sinkhole collapse incidents experienced along most highways in karst areas are usually the soil collapse type (Fig. 6a, b, c, d, and e) as defined by [24] for sections of East Tennessee karst. Extremely rare are occurrences of bedrock collapse into large open caves; however, they do occur.

### Karst Features and Highway Construction

There are a number of features that characterize the karst landscape that can, and often do, present problems for highway engineering projects. Features such as subsidence depressions (no visible cave opening) and sinkholes should be considered in any planning study. Likewise, known cave systems, springs, “dry valleys,” and areas of numerous limestone outcrops should be closely studied. Potholes, sinkholes that receive surface streams, and flooded or water-filled sinkholes and



**Karst Terrane and Transportation Issues. Figure 5**

Naturally occurring sinkholes often expose limestone bedrock as shown in this photo from Middle Tennessee

depressions should be avoided if at all possible. Large karst valleys known as uvalas and poljes may be overlooked due to their enormous size relative to other karst features.

Building roadways over existing sinkholes and other karst features is obviously not the preferred engineering choice. However, when building roads across karst areas these features are often unavoidable. The construction practice of dumping soil into a depression or sinkhole without proper investigation and design procedures will usually result in subsidence of the fill.

### Collapse

One of the most recognizable features of karst is sinkholes. The result of human activity on the karst landscape often includes subsidence or collapse of a building, roadway, house, or even a yard (Fig. 7). When subsidence develops beneath structures or highways, it may have a catastrophic impact resulting in high repair costs.

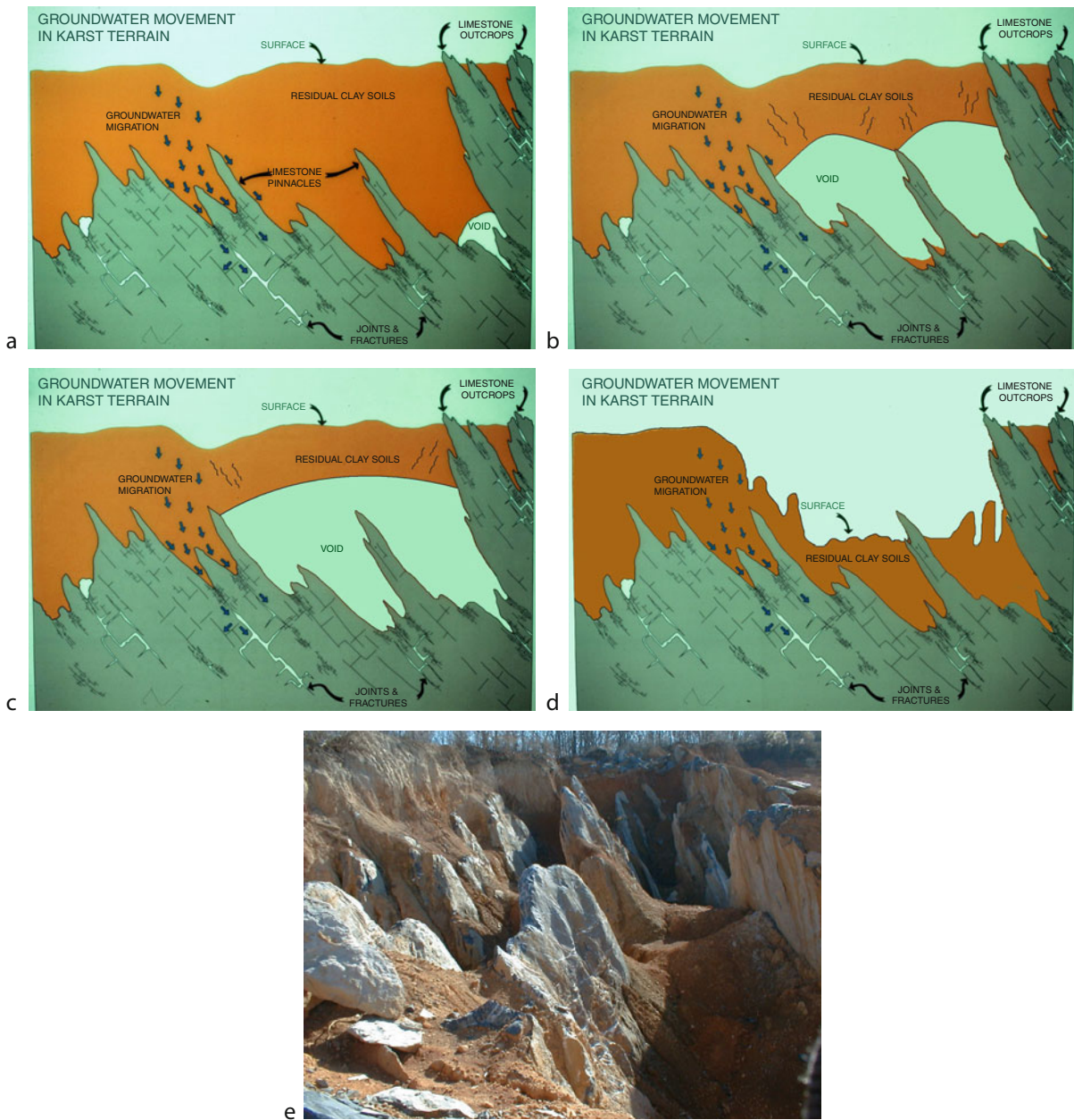
The construction and maintenance of highways and appurtenant structures in karst terrane often will trigger sinkhole collapse, subsidence, and flooding. The collapse of highways in karst areas has been well documented in the literature [18, 21, 22, 27, 33].

The relationship between construction activity and the occurrence of sinkholes has also been documented [17, 34, 37]. More specifically, Moore [22, 24] relates the occurrence of sinkhole collapses to highway construction, particularly the grading and ditching operations where surface and subsurface water flow paths have been altered. Studies conducted by Moore [24] cited above show that over 75% of the sinkhole collapses that have been documented along the roadways by the Tennessee Department of Transportation (TDOT) in East Tennessee were found to have occurred in the drainage ditch of the roadway.

Sinkhole collapse and flooding problems along Tennessee highways have been described by Royster [44] and Moore [22, 23]. In addition, Sowers [46], Newton [33], Foose and Humphreville [11], and Amari and Moore [1] have detailed possible geotechnical solutions to subsidence, flooding, and groundwater contamination in the Valley and Ridge Province from Alabama to Pennsylvania.

In 2003 Moore updated the 1987 study by analyzing 163 cases of sinkhole collapse incidents in East Tennessee between 1969 and 2002. Of the 163 sinkhole incidents studied, 86.5% of the sinkhole occurrences were located in highway ditch lines [27]. The 2003





**Karst Terrane and Transportation Issues. Figure 6**

This sequence of drawings shows a hypothetical development of a cover collapse type sinkhole, common in much of the karst areas of the eastern USA: (a) shows void developing in the residual soil covering tilted limestone; (b) shows the void becoming larger and spanning between two rock pinnacles; (c) shows a larger soil bridge over the void; (d) shows the result of the soil bridge collapsing into the void below, causing a cover collapse sinkhole; and (e) shows a real example of the collapse as depicted in the above drawings



**Karst Terrane and Transportation Issues. Figure 7**  
Some sinkholes are often filled with trash and other debris which leads to the contamination of the surrounding groundwater

study also supported the findings of the 1987 study by showing that of the ditch line collapse incidents analyzed, 93% also involved unlined ditches (the same percentage disclosed in the 1987 study).

### Warning Signs of Collapse

Catastrophic sinkhole collapses can engulf entire houses and sections of roadways. Predicting sinkhole development can be extremely challenging.

However, evidence of subsidence is sometimes evident prior to catastrophic sinkhole formation. One of the initial signs of collapse sinkhole development is the initially minor subsidence of an area. The effects of minor or initial subsidence are often evident. Minor pooling of surface water may occur in normally dry areas. Shallow puddles of water on a highway surface or along a ditch line are also initial signals of possible collapse.

Signs of settlement around houses and other structures may indicate subsidence. Cracks in house foundations, bridge abutments, or piers are signs of subsidence. The tilting of trees or other vegetation also indicates movement of soils. This type of evidence is often associated with landslides, but can develop in association with catastrophic sinkhole collapse.

Under most conditions these early warning signs may develop over a considerable amount of time

(months or even several years). In construction areas, induced sinkholes may occur suddenly without any indication of an impending collapse.

The formation of a sinkhole in a natural setting or on a construction site may occur in a sequence of settlement, significant subsidence, and collapse. Settlement of the ground may be noticed at first where minor movement of the soil, on the order of a few centimeters, may occur. Subsidence usually follows with drastic and very noticeable downward warping of the ground surface but with no large-scale cracks or scarps, sometimes many meters in diameter, but with no actual surface collapse of soil or bedrock. Finally, a sinkhole results from the collapse of the overlying soil (or bedrock) into the void below. This sequence may occur over a long period of time (months to years) or may occur quickly in a matter of hours.

### Sinkhole Formation in Roadway Ditches

The greatest number of karst problems that develop along highways in East Tennessee involves subsidence and collapse of the drainage ditch (Fig. 8). These karst problems are referred to as being “induced” by some type of construction activity as opposed to being naturally developed [34].

In most highway design situations, roadway ditches with gradients of 3% or less, are designed to be left barren or sodded. Only when the ditch line gradient exceeds 3%, according to most standard roadway design procedures, are the ditches paved or treated with an impervious material (i.e., concrete, polyethylene, geofabrics).

Within karst areas, the problem with untreated ditches often results when run-off accumulates in the ditch line and percolates into the underlying soil and rock. As the surface water migrates downward, clay particles are taken from the soil and carried into existing solution channels in the top of the bedrock and into the underlying bedrock conduits and caves. A cavity develops in the soil mass (above the bedrock) and enlarges from the bedrock toward the surface over a variable period of time (Fig. 9). Where the soil can no longer span the subsurface void, then the soil mass collapses into the underlying cavity and the collapse progressively works upward to form a surface depression or a collapse sinkhole [10].





**Karst Terrane and Transportation Issues. Figure 8**  
Sinkholes often form along highway ditchlines as surface water is concentrated there leading to the subsurface erosion of the soil which forms these sinkholes



**Karst Terrane and Transportation Issues. Figure 10**  
When roadway bridges are constructed in karst terrane, sinkholes can develop beneath the supporting structures as shown here along I-24 in Montgomery County, Tennessee



**Karst Terrane and Transportation Issues. Figure 9**  
Soil voids usually form over the limestone bedrock before the soil collapses forming a cover collapse sinkhole

Construction projects are notorious for disregarding the surface runoff and usually result in serious siltation problems. In addition, the pooling of surface run-off in recently graded or excavated karst areas can result in sinkhole collapse. A significant aspect to consider is the new drainage path along the grade of the roadway (a drainage ditch) that concentrates the runoff and increases infiltration into the subsurface. An example of this process occurred on a highway construction project in Montgomery County, Tennessee, where surface runoff from a rain event was allowed to pond around newly constructed

bridge pier footings on I-24. The concentration of water on the freshly excavated ground (which happened to be in an active karst area) triggered a collapse (Fig. 10) of residual clay soils around the pile-supported footings [44].

### Drainage

Other types of karst features and hazards are associated with drainage issues. Flooding and groundwater pollution problems are two major concerns associated with drainage in karst.

Flooding of highways constructed across sinkholes is a relatively common occurrence in some karst areas. A number of sinkhole flooding problems of this type have been studied and documented (Tennessee: [16, 20, 22, 23]; and Royster [44]; Kentucky: [5]).

In most instances of highway flooding, the subject road was constructed across (or into) the sinkhole following the natural topography (Fig. 11). Prior to construction, land use may have been agricultural with little runoff and the sinkhole did not flood. Many such sites are now urbanized and the sinkhole can no longer adequately drain the increased runoff.

Groundwater pollution due to the infiltration of highway surface runoff into a sinkhole feature has become a major environmental concern associated with highway routes in karst. While a number of researchers have studied the effects of highway runoff



**Karst Terrane and Transportation Issues. Figure 11**

Roads built across and in sinkholes may flood if the subsurface drainage becomes blocked as shown in this photo of Prosser Road in Knoxville, Tennessee

on the surface environment, few have dealt with the effects on the subsurface environment. Quinlan and Ewers [40] and Quinlan and Ray [42] discuss the effects of surface runoff on the Mammoth Cave System and their efforts to dye-trace the karst boundary. In their discussions, it was pointed out the necessity to map and dye-trace all sinkholes connected to roadways that traverse through the Mammoth Cave National Park.

Stephenson and Beck [48] made a review of literature regarding the quality of highway runoff and its potential impacts on karst groundwater. They found that little attention was being given by researchers to the issue of groundwater contamination by highway-related surface runoff, and that the highway runoff could contain high concentrations of hydrocarbons and other vehicle-related contaminants.

In 1997, Stephenson and Beck describe the results of a Federal Highway Administration Pooled Fund Study (that involved 15 state DOTs including Tennessee) where a prototype filtration system (Fig. 12) was designed to treat highway runoff in an interchange of I-40 and I-640 in the eastern part of Knoxville,

Tennessee. This study described the attention that is required by infrastructure designers to prevent or lessen the pollution of the groundwater system in karst areas.

### Reactive Approaches and Remedial Measures

Historically, the remedial approach to karst-related highway subsidence and flooding problems has typically been reactive in nature. Road crews commonly repair the sinkhole collapse after it has happened.

Remedial measures used in correcting karst-related subsidence problems reactively (after they occur) may be divided into three areas: bridging, drainage, and relocation. The techniques used in bridging include graded-rock and shot-rock pads and fills, graded-rock backfill, concrete structures, and grouting [22, 25, 47]. Remedial measures used in drainage include alteration of the existing drainage by the use of paved or geomembrane-lined ditches, special overflow ditches, plastic overlays, pumps, horizontal drains, and the maintenance of obstructed sinkhole entrances. Surface drainage filter systems have been researched and are



**Karst Terrane and Transportation Issues. Figure 12**

Surface runoff from roadways can be filtered to remove pollutants before the water reenters the groundwater system through sinkholes

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beginning to be employed to treat surface runoff from highways in karst areas. Although not widely used, relocation of the highway facility around a karst area may also be a viable corrective measure.

### Types of Bridging Remedial Approaches

The treatment of karst-related subsidence and collapse features involving engineered structures can include methods as varied and site specific as the sinkholes themselves. Many remedial treatment techniques involve a method of “bridging” to provide adequate stability and bearing capacity.

There are a number of different approaches to bridging that can be applied. These include, but are not limited to, the following: conventional bridge spans, “muck trestles” (bridge built on grade), drilled shafts, riprap backfill, rock pads, grouting, concrete slabs, geofabrics, and geogrids. In some instances, a combination of these procedures may be needed [29].

Where field conditions warrant, a concrete structure may be used to bridge or span the collapse sinkhole area. This remedial measure may entail the construction of: (1) a free spanning highway concrete or steel

bridge; (2) a concrete bridge with the deck constructed on the ground surface (commonly referred to as a “muck trestle”); (3) drilled cast-in-place concrete piers to support a concrete slab or bridge section; or (4) a concrete slab placed over the subsurface opening [29].

Although a very costly approach, a free spanning bridge constructed over the sinkhole area is very effective in eliminating future problems. This approach should be considered when crossing very large and deep sinkholes or in environmentally sensitive areas such as Mammoth Cave National Park.

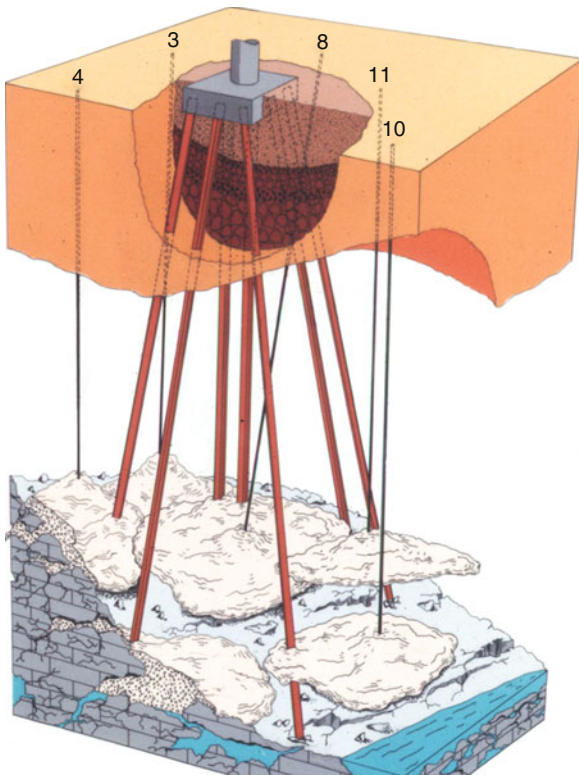
The “Muck Trestle” bridge has been considered for a severe karst-related flooding and collapse problem in Hamblen County along State Route 34 near Morristown. This concept was applied to a railroad bridge in the same vicinity of Hamblen County where a sinkhole collapse was endangering a rail line [50].

An often recommended measure for structural foundations in karst strata is the use of drilled cast-in-place piers (caissons). Where soluble limestone strata occur beneath a river channel, numerous cavities may exist which are either clay filled or open. In some instances, a series of solution cavities may extend downward to depths of over 30.4 m (100 ft). Karst



strata that extend as much as 8–10 m (25–30 ft) below the surface can make excavation prohibitive and drilled cast-in-place piers more viable.

Another type of bridging concept commonly used in roadway applications is to use concrete grout to seal up cavernous strata. Grouting is often used at the soil/rock interface to close up openings that the soil may filter into – this is referred to as “cap grouting.” Royster [44, 45] used this concept to repair a bridge footing along I-24 in Montgomery County, Tennessee where a collapse occurred beneath a pier footing pile cap (Fig. 13). Another instance of using grouting to repair subsidence and sinkhole collapse problems is detailed in Mellett and Maccarillo [19] where the authors warn that grouting can divert underground water flow into other areas, and new sinkholes may occur nearby



**Karst Terrane and Transportation Issues. Figure 13** “Cap grouting,” where concrete grout is pumped down to the soil–bedrock interface to seal the rock surface and prevent the migration of soil down into cavities in the bedrock, was used on a bridge footing in Montgomery County, Tennessee along I-24

as a result. As shown in the above example, caution should be used when attempting to use grouting as a method of stabilization of collapse problems.

The Tennessee Department of Transportation applies another effective type of bridging concept which uses rock riprap to backfill the collapse. The interlocking action of the riprap backfill, often referred to as “chunk rock” backfill,” and the placement of the backfill on the top of the in-place bedrock effectively bridge the solution cavity (Fig. 14). This concept also provides a free draining structure for groundwater and surface drainage.

These inverse filters using “chunk rock” backfill are designed to prevent overlying materials from filtering down into the interstitial spaces of the clean rock backfill and solution cavity resulting in subsidence or even another collapse.



**Karst Terrane and Transportation Issues. Figure 14** Clean graded rock is used to backfill a sinkhole collapse along Interstate 640 in Knoxville, Tennessee by the Tennessee DOT



**Karst Terrane and Transportation Issues. Figure 15**  
A rock pad is constructed over naturally occurring sinkholes on a road project in Tennessee. The rock pad provides not only stability for the road but allows surface drainage to flow into or out of the sinkhole, which had bedrock exposed and not soil

A bridging technique, commonly used in Tennessee, consists of a limestone graded rock pad placed to span an area of intense solution activity (Fig. 15). This technique was used on a section of Tennessee State Route 1 (U.S. 11-W) in Hawkins County where a new four-lane section of State Route 1 was constructed over an area of active sinkholes. This rock pad provided stability for the highway by allowing groundwater to flow freely from the sinkholes to a special channel and box culvert.

The rock pad constructed over this sinkhole area has a minimum thickness of 1.5 m (5 ft) and meets the following rock specifications [29]:

Rock pad material consists of sound, nondegradable limestone with a maximum size of 0.9 m (3 ft) and is free of shale and/or clay; at least 50% (by volume) of the rock is uniformly distributed between 0.3 m and 0.9 m (1 ft and 3 ft) in diameter, and no greater than 10% (by volume) is less than 5 cm (2 in.) in diameter; the rock material is roughly equi-dimensional; thin slabby material is not accepted.

A geotextile filter fabric should be used to separate the rock pad from the overlying fill material (usually soil). The filter fabric specifications should be determined based on the grain size of the overlying fill material.

## Drainage-Related Remedial Approaches

The development of proper drainage systems for highways constructed across karst terrane is commonly overlooked, often necessitating reactive approaches to karst drainage problems which involve ditch line collapse and flooding.

A successful technique of drainage control involves the use of lined drainage ditches along roadways in karst areas. This includes using materials such as asphalt, concrete, or geomembrane-lined drainage ditches. Studies [24, 27] have shown that the majority of collapse-type karst problems occur in unlined ditches. Unlined ditches are usually sodded at best and have gradients of less than 3% and more often 1% or less.

Unpaved ditches also provide for increased seepage which may result in subsurface erosion and finally collapse. Bare soil ditches and even sodden ditches are prone to this type of collapse failure (Fig. 16).

Usually, water collecting in an unlined ditch will seep into the underlying soil eventually reaching a conduit developed at the soil/bedrock interface below the ditch. Erosion continues until the soil over the cavity collapses; the result of the erosion being a collapse sinkhole induced by seepage from the drainage ditch. The solution is to line the ditch with an impervious material at the outset, during construction.

Materials that have historically been used to line ditches include sodding, asphalt, riprap, and concrete. Concrete paved ditches have historically been used in these situations and perform moderately well.

In recent years, new emphasis has been put on the use of synthetic geomembranes (Fig. 17). Their use as ditch liners in karst areas is strongly recommended due to the following factors: flexibility, imperious character, strength against puncture, ease of installation.

The geomembrane liners can be installed with a soil or sod cover for aesthetics and UV protection. Riprap can also be placed atop the geomembrane (careful placement is required). In emergency situations, polyethylene sheeting can be used until a more permanent repair can be affected. Finally, if a concrete ditch is desired, the concrete should be applied over a geomembrane liner. Geomembranes that tend to perform well in these applications are 60 mil thickness HDPE and PVC membranes.



**Karst Terrane and Transportation Issues. Figure 16**  
Unlined drainage ditches in karst areas usually bear the brunt of sinkhole formation as shown in this photo of a sinkhole along State Route 72 in Tennessee



**Karst Terrane and Transportation Issues. Figure 17**  
Geomembrane is used for drainage ditches along some highways in karst areas of Tennessee. Most are covered with riprap or concrete paving

### Relocation

In some instances relocation of the highway is the best alternative to solving the karst-related problem. This may simply involve shifting the roadway slightly to miss a specific sinkhole or cave entrance. In other cases, the relocation may be several hundred feet from the original alignment and cost thousands of dollars for additional right-of-way.

### Proactive Measures

Being proactive in regard to dealing with karst in highway design and construction is to identify the problem

and formulate a design that will remediate that problem before construction begins. If a roadway alignment has to be located in sinkhole areas, then design roadway embankments and cut sections so that the impact of the karst on the roadway will be lessened or eliminated. Avoidance measures and some combination of drainage and bridging methods are usually the best direction to take in a proactive approach to designing and constructing highways in karst areas.

### Avoidance Measures

The avoidance of karst areas by transportation facilities is recognized as a highly desired approach in highway planning; however, the extensive suburban development necessitating new highway construction commonly limits highway corridors to less desirable land. Identification of the most severe karst areas (with respect to drainage, sinkhole collapse, and other environmental impacts) during location and design phases of highway planning can lessen the impact of karst features on the project and result in a better designed and more stable roadway facility.

Avoidance is only effective where karst is active and recognizable. The construction of new roads with associated increases in runoff along the new landscape can trigger subsidence and flooding problems where previous land uses were in relative equilibrium with the karst.

Locating new roads in areas prone to karst development requires a great dependence upon the geologic information that is available. The geotechnical information gathered during the investigative phase of a proactive approach to highway design is most valuable in determining route location selection relative to karst. Maps and other information that delineate such karst areas (derived from a proactive investigation) can be used to avoid problem areas. The use of geophysical methods such as resistivity, seismic, and radar can be used to aid in the characterization of subsurface conditions in karst areas [3].

Caution should be exercised when using standard 7.5 min U.S.G.S topographic maps to identify sinkhole prone areas. The standard 20 ft (6 m) contour interval used with the 7.5 min quadrangle rarely reveals the true number of sinkholes present. Hubbard [13] researched this issue in the karst regions of the Valley and Ridge of Virginia where he consistently identified more



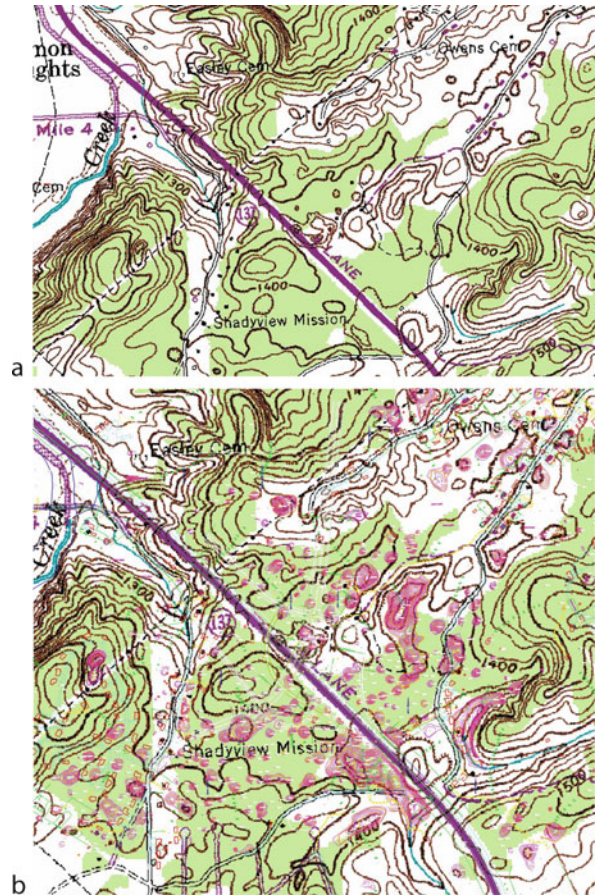
sinkholes on the ground than were depicted on selected 7.5 min quadrangle maps. In one instance, Hubbard describes a 7.5 min quadrangle with a 20 ft contour interval that revealed 55 sinkhole features, while ground field mapping identified 533 sinkhole features.

In another case that relates this concept to East Tennessee, Moore [28] studied a proposed location of an interchange along I-181 in Sullivan County, Tennessee situated in the Valley and Ridge province and underlain by carbonates. Within an approximately 100 acre site, the standard 7.5 min maps with 20 ft contour intervals revealed some 30 or so sinkhole features. After aerial mapping using a 1 m contour interval, a total of 177 sinkholes and 7 cave entrances were identified at the proposed site (Fig. 18a, b), which was later rejected by the Tennessee Department of Transportation for the interchange location.

Roadway designs may involve the use of broad horizontal curves to miss a sinkhole area or cave complex resulting in a more scenic facility. An example of this process is the Pellissippi Parkway Extension (I-140) in Knox County, Tennessee. The extension of a limited access, four-lane highway facility, “The Pellissippi Parkway” (I-140), involved the possible location of corridors in active karst areas of Knox and Blount counties in East Tennessee. Geotechnical involvement in the location and design phases of this highway development process resulted in the recognition of several unstable areas of karst and led to the adoption of remedial and preventive design measures which were incorporated into the construction plans [23].

Ultimately, the route selected was the most favorable geologic setting of the four proposed routes. Significant consideration by administrative officials was given to the geologic evaluation of the project, a measure of the progress in recognizing and addressing karst processes and teamwork within the geologic and engineering professions.

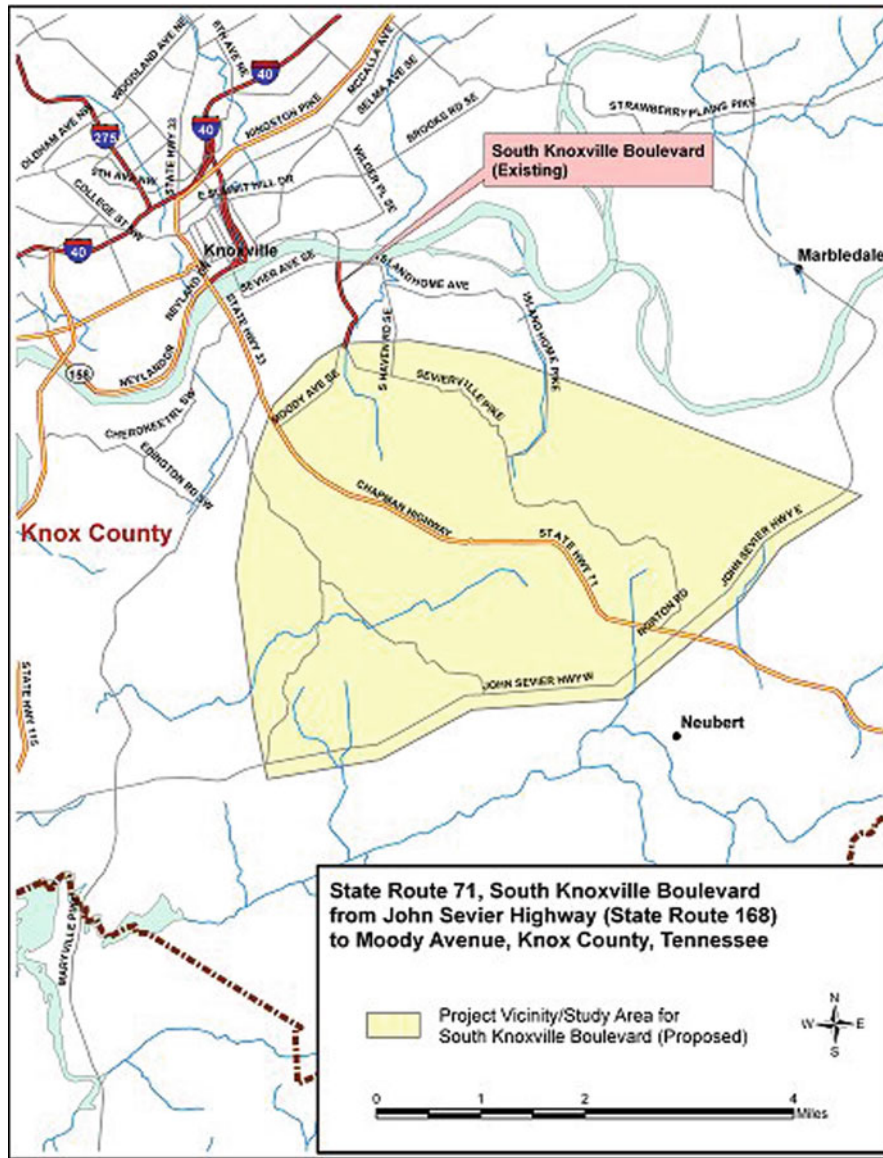
Mapping karst areas for planning use by government highway organizations (state DOTs) is very proactive and effective in reducing the impact of karst on proposed transportation routes. One such example is the South Knoxville Boulevard Extension (SR 71) in Knox County, Tennessee. The Tennessee Department of Transportation (TDOT) is planning a new roadway alignment (SR 71) that crosses portions of South Knoxville in East Tennessee. The proposed corridor



**Karst Terrane and Transportation Issues. Figure 18** Using topographic maps is a good source for finding sinkhole terrane. However, the scale of map and the contour interval can be deceiving as shown in the map above. Map (a) shows an area on a 20-foot contour scale with some 30 sinkholes developed; map (b) shows the same area on a 3-foot contour scale showing over 100 sinkholes

is located in a section of the Valley and Ridge Province of East Tennessee where several ridges and valleys will be crossed, as well as creeks, roads, subdivisions, and rural lands. The proposed corridor connects the current terminus of SR 71 at Moody Ave. in South Knoxville to John Sevier Highway (SR 168) (Fig. 19).

In an attempt to properly evaluate the potential for geologic hazards along the project, an effort was made to locate all sinkholes and caves within the project area,



**Karst Terrane and Transportation Issues. Figure 19**

This map shows the study area for the extension of the SR 71 – South Knoxville Blvd. in Knoxville, Tennessee. The study area contains a large karst sinkhole area shown on [Fig. 23](#)

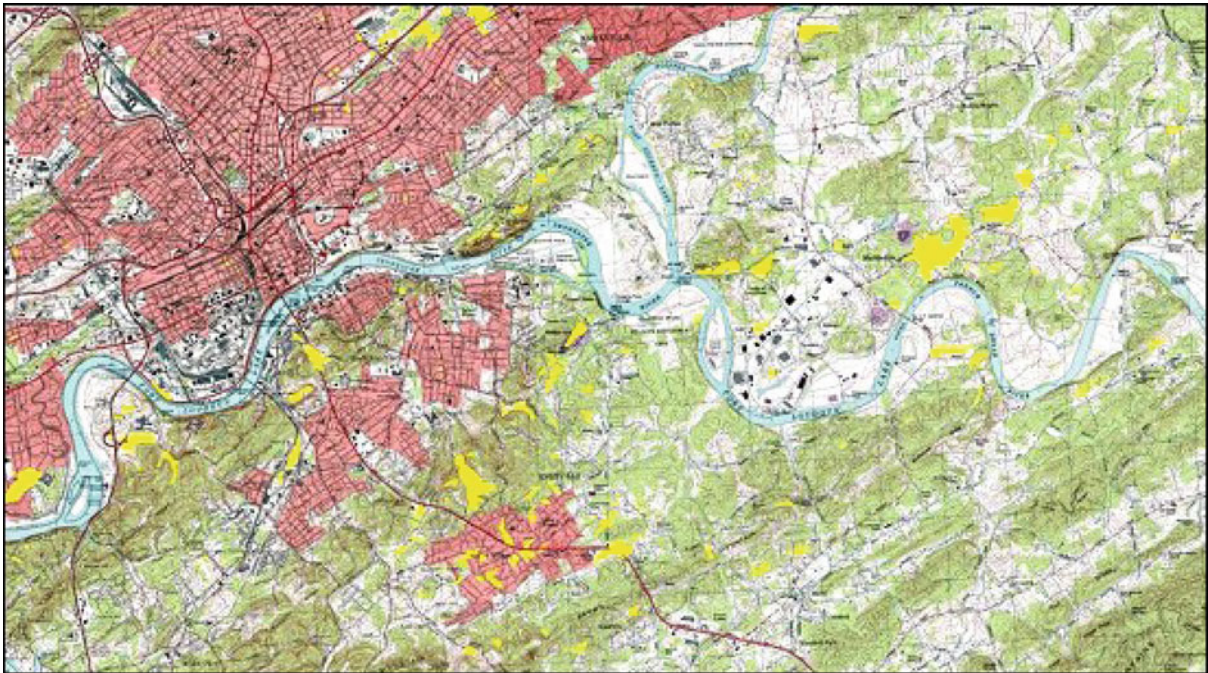
karst being the primary geologic hazard identified. To this effort, a karst map and a map of one cave was completed ([Figs. 20 and 21](#)).

The proposed SR 71 corridor is situated in the rolling to hilly topography of the Valley and Ridge Province of East Tennessee and includes a portion of South Knox County. Geologically, the corridor is situated in terrain underlain by folded and faulted middle-Ordovician sedimentary strata composed of several

major rock types including limestone, shale, sandstone, and siltstone.

The weathering of the rock strata has produced a knobby terrain that follows the out crop pattern of the specific formations, especially the Holston and Chapman Ridge formations. The weathering has also produced classic karst topography characterized by sinkholes, disappearing streams, and caves, including Meades Quarry Cave ([Fig. 22](#)).





**Karst Terrane and Transportation Issues. Figure 20**

This map shows sinkholes (yellow) that were found in the study area for the proposed SR 71 – South Knoxville Blvd. Extension in Knoxville, Tennessee

A geohazards evaluation was conducted by the Tennessee DOT Geotechnical Engineering Section for the proposed SR 71 route. This study was an effort by the Tennessee DOT to identify the geologic hazards along the corridor and to avoid or reduce the hazard impact on the roadway facility, environment, and the public. The main geohazard found along the proposed SR 71 study area was karst.

The study revealed that the corridor is characterized by features such as sinkholes, caves and cave entrances, sinking streams, and outcroppings of weathered carbonate rock (limestone and dolostone). The recognition of areas of active karst subsidence and collapse is of considerable importance to the design and implementation of the proposed highway infrastructure, SR 71.

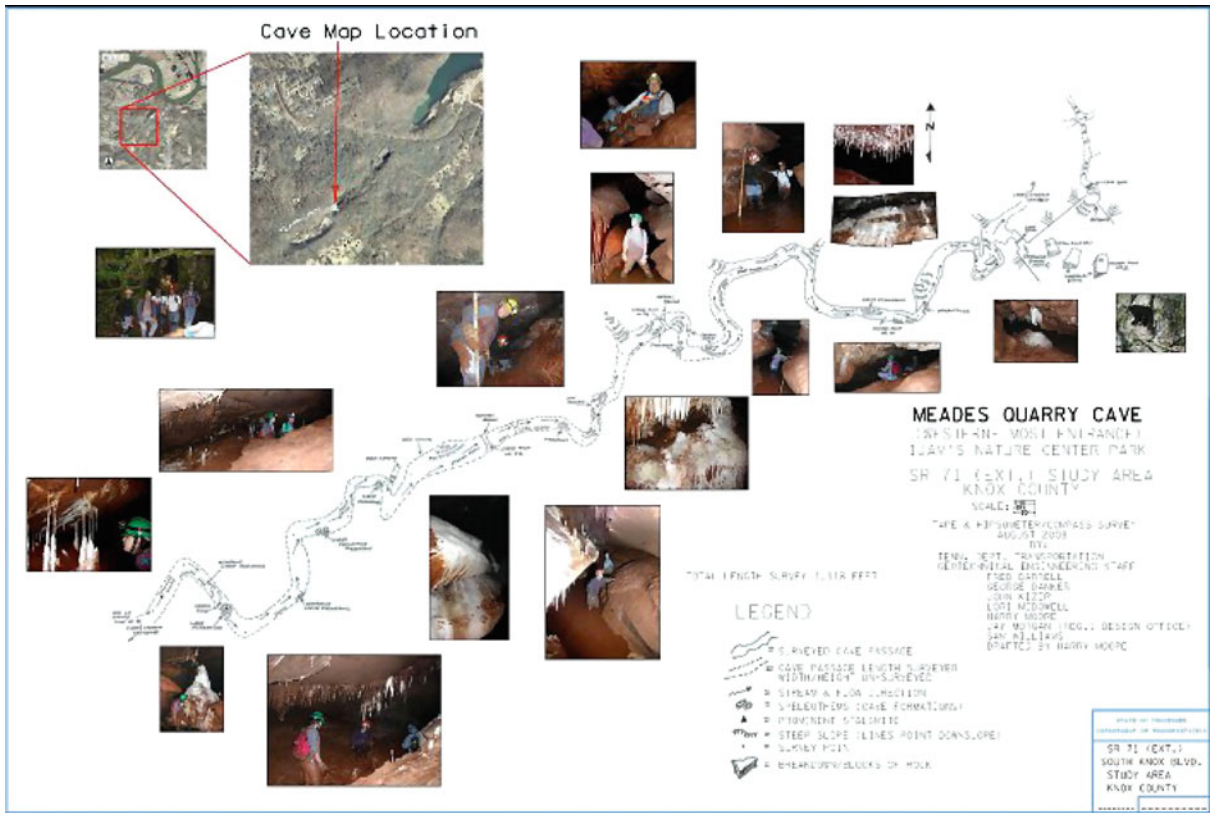
TDOT initiated a karst geohazards inventory and assessment to assist in evaluating and selecting a satisfactory alignment within the corridor study area. This study involved the location of caves and sinkholes within and adjacent to the proposed corridor. In addition, the caves were visited and preliminarily evaluated as to their geotechnical and environmental

importance. The caves that were found to be of significance to the proposed stability of the roadway or have environmental and archeological significance were surveyed to determine their lateral and vertical extent. Mapping of the caves was performed by both TDOT Geotechnical Engineering staff and local speleologists.

Caves and sinkholes offer special challenges relative to both the physical and environmental issues of highway development. The karst geohazards inventory study, which included mapping karst features, disclosed the presence of both sinkholes and caves, some of which may have detrimental structural, geologic, and environmental issues for alignment and grade design considerations.

Efforts to avoid karst areas with roads and other developments are difficult at best, especially since the “good” land is already mostly developed, leaving only the geologically undesirable land for current development. Geologically undesirable land includes such areas as karst terrane steep terrain, very rocky terrain, landslide-prone areas, soft ground, and areas prone to acid mine drainage, to name a few.





**Karst Terrane and Transportation Issues. Figure 21**

Cave maps, such as this detailed cave map of Meades Quarry Cave in South Knoxville, Tennessee can be used by highway designers to avoid impacting fragile cave environments when planning and designing future roads

In planning new highway corridors certain constraints must be known and when identified are usually displayed by mapping. The Tennessee Department of Transportation, Geotechnical Engineering Section is involved in studying proposed roadway corridors in East Tennessee in an effort to identify geohazard areas.

The mapping of karst areas generally involves the following procedure as outlined by Moore and McDowell [30]:

- In general, 7.5 min topographic maps (that use a 6 m (20 ft) contour interval) are used to locate karst features such as sinkholes (closed depressions on the contour map), caves, springs, and sinking streams. Once these karst features are identified and located on the topographic maps, then a field reconnaissance is performed to field check the features to make sure that they are there.

- Afterward, the sinkholes and other karst features are enhanced on the topographic maps and subjective boundaries are drawn to encircle these areas. Typically, these encircled areas are identified as “areas of high concentrations of sinkholes” and/or “areas of numerous cave openings.” Actual cave entrances are not plotted on the final geohazard map due to access issues and private owner protection.
- The geohazard areas are then expressed as outlined patterns on topographic maps to better illustrate the geohazard relative to the surrounding landscape. In addition, the proposed corridor route is overlain on the geohazard map. This map is then used by the roadway planners to better locate the final roadway centerline.

In addition to the surface mapping of sinkholes, it is becoming more important to map the caves where they may exist in close proximity to the proposed roadway.



**Karst Terrane and Transportation Issues. Figure 22**  
This photo shows the man-made entrance to Meades Quarry Cave which was opened by marble quarrying operations in South Knoxville in the early 1900s

By knowing spatially where the cave passages are located, a more accurate design of proposed roadway cut slopes can be made. This would prevent the unnecessary opening of a cave system to the surface, and benefit the cave biota, such as bat colonies and salamanders to name a few.

The use of experienced cavers (usually cavers who are members of the National Speleological Society, NSS) in combination with engineering survey crews provided the best results for locating the cave passages spatially with respect to the proposed roadway. It is anticipated that mapping of cave passages will become increasingly mandatory as society continues encroaching onto and into the karst environment.

After a review of available geologic data and field investigations, the SR 71 Extension corridor in South Knoxville, Tennessee was found to be located within several strike belts of karst. The belts of karst trend in

a northeast to southwest direction, reflecting the strike of the underlying bedrock. In addition, the rock strata are folded into a large structural anticline resulting in the bedrock forming a “U”-shaped pattern in the South Knoxville community (Fig. 23).

Numerous sinkholes and caves were found to be located in these karst areas. A map of the most intensive sinkhole areas was prepared in order to better assess the corridor terrain. A field reconnaissance of the study area was made in an effort to locate as many of the sinkholes as possible. Many were overgrown and difficult to locate. A few of the caves that were identified were found to be located outside of the numerous sinkhole zones (outlined on the attached karst-sinkhole map), but within typical karst terrane.

The possible impacts on the karst environment from constructing the proposed road alignment (or any other structure, building, subdivision, etc.) include sinkhole collapse, sinkhole flooding, groundwater contamination, and environmental effects on the cave and subsurface-dwelling wildlife, such as bats and salamanders.

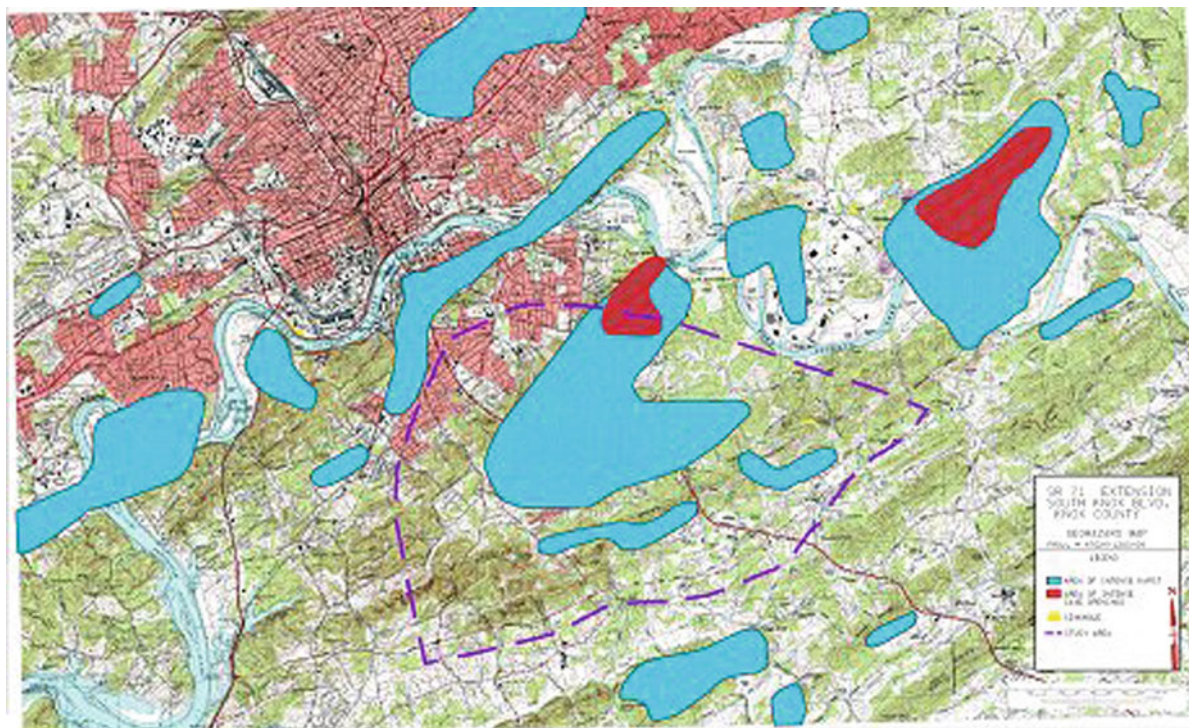
### Mapping Subsurface Karst: Meades Quarry Cave Mapping Initiative

Due to the uncertainty of the existence of Meades Quarry Cave within the proposed study area, it was decided to map the western-most portion of the cave system. The purpose of mapping the cave was to determine if the general trend of the cave and cave stream is toward the sinkhole area around Old Sevierville Pike and Red Bud Drive, which is within the study area of the proposed parkway extension.

The presence of the Berry Cave Salamander (*Gyrinophilus gulolineatus*, a subterranean amphibian listed as a potential threatened species – see Fig. 24) in the Meades Quarry Cave stream has made the cave an important issue of the overall study of the proposed SR 71 extension. The Berry Cave Salamander derives its nutrition from debris and organics that are flushed into the sinkholes by rain events which in turn recharge the cave stream in which the salamander lives. Adversely affecting the sinkholes would directly affect the salamanders.

As a result of the concern over the salamander species found in Meades Quarry Cave, it was decided by Tennessee DOT that a mapping effort of the





**Karst Terrane and Transportation Issues. Figure 23**

This map shows the karst and sinkhole area that was mapped by the Tennessee DOT Geotechnical Engineering Section while studying the proposed extension for SR 71 – South Knoxville Blvd. in Knoxville, Tennessee. The dashed area shows the actual study area (base geologic information from Hardeman [12])

cave would be completed. In August of 2008 the Geotechnical Engineering Section initiated an effort to map the western-most portion of the Meades Quarry Cave system (Figs. 25, 26, and 27). This section of the cave system has its entrance in the floor of an old quarry pit which exposed the cave during quarrying operations in the 1930s and 1940s.

As a consequence of our investigation and mapping initiative, it was interpreted that the stream passage of Meades Quarry Cave does indeed lie within the study area of the proposed SR 71 highway extension. In addition, it was decided that a dye trace study was needed to further delineate the groundwater recharge area for Meades Quarry Cave system.

### Dye Trace Study

A proven and reliable method of identifying subsurface drainage areas in karst is to use dye tracing. Many studies have disclosed the valuable usefulness

of dye tracing (Quinlan and Ray [39–42]). To that end, the South Knoxville SR 71 highway project study has initiated a dye trace study of the proposed highway route in a sinkhole prone section of the corridor.

As noted in the above discussion, the Meades Quarry Cave system of solution channels and stream(s) is located within the study area for the proposed extension of SR 71. Also, it was disclosed by local University of Tennessee biology researchers that the Meades Quarry Cave contains a population of Berry Cave Salamander which is a rare species of animal (Moore and McDowell [30]).

The U.S. Fish and Wildlife Service and the Tennessee Wildlife Resources Agency has noted the presence of the Berry Cave Salamander in the Meades Quarry Cave system and requested that TDOT do an adequate dye trace study of the sinkholes in the area of the proposed project to better understand the geohydrology of the Meades Quarry Cave system. The dye trace study is to better differentiate which sinkholes actually recharge





**Karst Terrane and Transportation Issues. Figure 24**  
This photo of the Berry Cave Salamander made in Meades Quarry Cave in South Knoxville, Tennessee. Cave environments are fragile places and harbor many rare and endangered species of wildlife. (Photo by Matt Niemiller [36] University of Tennessee; from: <http://www.herpetology.us/niemiller/>)

the cave stream that the Berry Cave Salamander lives in, so that TDOT can avoid any impact on the cave system with the construction of the proposed SR 71 extension. A result of the dye trace study will be an effort to minimize the impact of highway runoff on the local karst system. This will be accomplished with the use of runoff filtration systems.

In summary, the study of the karst of the SR 71 project found that the proposed corridor has numerous karst features that are found within the area topography. Mapping surface and subsurface karst features can greatly aid the evaluation of proposed roadway corridors. A result of this study was the development of a surface karst map which showed areas of numerous sinkholes, which is interpreted as areas of potential future sinkhole development.

The construction of road projects, as well as industrial sites, shopping malls, and subdivisions will be problematic in karst areas and should be avoided when possible. However, if avoidance is not possible, then minimization of the impact of construction on the sinkhole and cave environments should be the objective. Such design measures as minimal cut and fill construction and minimal alterations in the surface



**Karst Terrane and Transportation Issues. Figure 25**  
Mapping caves is an important process in studying the location of future transportation routes like highways and railroads; shown is Meades Quarry Cave mapping by Tennessee DOT geologists

drainage of an area (both surface and subsurface) are recommended.

Another result of the karst geohazard study was the development of a karst planning map and the decision that mitigation of the impacts on the karst areas will need to be included with the roadway design and construction plans once the road project is approved. Proactive measures such as surface drainage filtration systems for sinkholes, impermeable lining for ditchlines (to prevent new sinkholes from forming), the use of graded rock embankments (for stability and groundwater impacts), and the use of structural bridges over sensitive sinkholes are recommended to be considered and/or employed during the roadway design phase.

The groundwater contamination issue is an important topic for the SR 71 project due to the potential



**Karst Terrane and Transportation Issues. Figure 26** Meades Quarry Cave contains a perennial stream that supports the environment for the Berry Cave Salamander



**Karst Terrane and Transportation Issues. Figure 27** Cave speleothems decorate a passage in Meades Quarry Cave in Knoxville, Tennessee. Shown are white soda straws connecting with white stalagmites

impact on the rare Berry Cave Salamander which lives in the Meades Quarry Cave system. Once the groundwater dye trace results are obtained by the Environmental Division (as discussed in the above narrative), then a more appropriate evaluation of the karst groundwater drainage can be made.

Surface water runoff filtration systems, as proposed for the SR 71 project in South Knoxville, have recently been constructed on a Tennessee DOT roadway project in Hamblen County, Tennessee where the runoff empties into a sinkhole (Fig. 28). The filtration system design was based on results of a FHWA Pooled Fund study that involved filtering highway runoff in karst areas. Tennessee DOT was a partner in the FHWA Pooled Fund study [48, 49].

It is important to understand that there will always be an impact on the karst environment (sinkholes, caves, wildlife, and groundwater) when construction occurs in karst areas. In some places, this impact may be significant where caves and sinkholes are exhumed and/or filled in with embankment material, and where surface drainage is directed into sinkholes that empty into the caves and groundwater systems. These impacts can be lessened by appropriate and judicious mitigation during the design and construction phase of the project.

### Proactive Drainage and Bridging Concepts

The proactive approach to karst-related drainage problems requires attention to several design-related items. These include lined ditches, rock pads, overflow channels, sinkhole opening improvement/protection, curbs for embankment sections, and drainage wells. The following discussion summarizes the treatment of karst-related drainage problems [28]:

- *Lined ditches* – The single most important item that can be implemented to prevent future sinkhole collapse occurrence is the use of lined drainage ditches. Types of liners that tend to function the best include 60 mil PVC and/or HDPE geomembrane, and concrete and asphalt materials.
- *Rock pads* – Rock pads beneath embankments using clean riprap limestone may be used for bridging depressions and sinkholes (Fig. 29).
- *Overflow channels* – This concept involves the construction of a lined channel or pipe from a negative





**Karst Terrane and Transportation Issues. Figure 28**

This shows the sinkhole filtration system constructed on a Tennessee DOT road project in Morristown, Tennessee. The filter is in the long rectangular structure near the top center of the photo. The sinkhole receiving the filtered runoff is in the *top left* of the photo



**Karst Terrane and Transportation Issues. Figure 29**

Shown is a roadway embankment that is underlain by an engineered rock pad across a sinkhole in Knoxville Tennessee



drainage area (sinkhole) to a positive draining system.

- *Sinkhole opening improvement/protection* – This concept involves improving the runoff flowing into subsurface cavities by removing debris and trees from around the throat of a sinkhole and protection of the cavity opening from siltation and debris using such methods as siltation barriers, debris catchment fences, riprap, gabion siltation barriers, and concrete structures (Fig. 30).
- *Drainage wells* – An additional concept that has been implemented in some areas is the use of injection drainage wells [7, 8, 22, 43, 44]. These types of storm water drainage wells are required to be permitted by the State and are known as Class V injection wells.

When implementing any of the above drainage concepts, it is imperative that a maintenance program be established and monitored in order to reduce future problems.

Another proactive method of approaching karst drainage problems is the use of tracer studies (dye, pollen, spores, etc.) in identifying the subsurface drainage regime [6, 39, 41]. As discussed earlier (and in more

detail) under proactive remedial measures – investigative measures – the use of tracers placed in the subsurface (via springs, wells, sinkholes, etc.) enables karst hydrologists to define the subsurface drainage basins and recharge areas.

The information gained through tracer studies is extremely useful in both design development and litigation, despite its time-consuming nature.

The use of sinkholes for drainage is often considered in roadway design. In a proactive methodology for environmentally sensitive roadway design in karst, the best approach would be to *avoid placing drainage into a sinkhole*, particularly using the sinkhole as a wastewater disposal feature. The use of sinkholes as drainage features is basically groundwater contamination by design. Eventually, hazardous waste will be spilled and the karst aquifer will become contaminated.

Concerns about groundwater contamination must be addressed by either a filtration system, a retention/sediment basin, or both. A study by Stephenson et al. [49] showed that using a pilot-researched peat-moss filtration system on highway runoff on the I-40/I-640 interchange in Knoxville, Tennessee (Fig. 31) effectively reduced the highway runoff contaminants by



**Karst Terrane and Transportation Issues. Figure 30**

When roadways are built in sinkhole areas, sinkhole may need to be used for draining the runoff. Shown here is one such sinkhole that was cleaned of debris and protected against erosion and siltation with riprap and straw bales



**Karst Terrane and Transportation Issues. Figure 31**

This shows the completed and functioning filtration system for a sinkhole that receives runoff from the I-640/I-40 interchange in East Knoxville, Tennessee. This is the prototype for such filtration systems that was the result of a Federal Highway Administration pooled fund study on filtering highway runoff in karst areas

90–99% [2]. This type of treatment of highway runoff is highly recommended for high-volume highways where the roadway runoff recharges karst aquifers via sinkhole features.

As discussed earlier under reactive remedial measures, there are a number of sinkhole improvement techniques that may be employed to ease the impact on the groundwater. These include siltation fences, trash racks, perforated and filter-cloth wrapped stand pipes, gabion revetment, erosion control geotextiles, riprap, and concrete structures such as box culverts and inlet structures.

Regardless of the type of method used to treat the sinkhole that is used for drainage, it is imperative that a maintenance program be established for the drainage facility. Without maintenance of the sinkhole improvement facility, silt and trash will eventually plug the sinkhole resulting in flooding.

### Future Directions

The collapse of roadway surfaces, drainage ditches, and bridge foundations, as well as numerous instances of flooding are karst-related issues and problems triggered by human construction activity on the environment. The greatest number of karst problems that develop along highways involves subsidence and collapse. This may involve the road or bridge footing itself

or a drainage ditch. In some instances, the construction can trigger sinkhole formation outside of the construction limits of a project.

Remedial measures used in correcting karst-related subsidence problems may be divided into three areas: bridging, drainage, and relocation. Avoidance measures and some combination of drainage and bridging methods are usually the best direction to take in a proactive approach to designing and constructing highways in karst areas.

Innovative and cost-effective remedial concepts for solving karst-related geotechnical problems require modifications and refinement of the standard design to insure proper results to site-specific conditions. Proactive involvement by the geologic and engineering profession will be necessary to insure the success of karst-related remedial design concepts proposed for highways.

### Bibliography

1. Amari D, Moore HL (1985) Sinkholes and gabions: a solution to the solution problem. In Proceedings of the 36th annual highway geology symposium, Clarksville, pp 47–68
2. Beck BF, Stephenson JB, Wanfang Z, Smoot JL, Turpin AM (1996) Design and evaluation of a cost effective method to improve the water quality of highway runoff prior to discharge into sinkholes. In Proceedings of the 1996 Florida environmental expo, Tampa, 1–3 Oct 1996, pp 155–164

3. Benson RC, Yuhr L, Kaufmann R (2003) Some considerations for selection and successful application of geophysical methods. 3rd international conference on applied geophysics, geophysics 2003, Orlando, 8–12 Dec 2003
4. Black TJ (1984) Tectonics and geology in karst development of Northern Michigan. In: Barry B (ed) *Proceedings of the 1st multidisciplinary conference on sinkholes*, 15–17 Oct 1984, Orlando, p 87–91
5. Crawford NC (1981) Karst flooding in urban areas, Bowling Green, Kentucky. *Proceedings of the 8th international congress of speleology*, Western Kentucky Univ., Bowling Green
6. Crawford NC (2003) Karst hydrogeologic investigation for proposed Kentucky trimodal transpark. In: Barry B (ed) *ASCE Special Publ. No. 122, sinkholes and the engineering and environmental impacts of Karst*, Huntsville, 6–10 Sept, pp 385–403
7. Crawford NC, Groves CG (1984) Storm water drainage wells in the karst areas of Kentucky and Tennessee. U.S. Environmental Protection Agency and Center for Cave and Karst Studies, Bowling Green, Kentucky, p 52
8. Crawford NC, Groves CG (1995) Sinkhole collapse and groundwater contamination problems resulting from storm water drainage wells on karst terrain. In: Beck B (ed) *Karst Geohazards*, *Proceedings of the 5th multidisc. conf. on sinkholes*, Gatlinburg, pp 257–264
9. Donaldson CW (1963) Sinkholes and subsidence caused by subsurface erosion. *Proceedings, 3rd regional conference for Africa on soil mechanics and foundation engineering*, pp 123–125
10. Drumm EC, Yang MZ (2005) Preliminary screening of residual soil stability in karst terrain. *Environ Eng Geosci* XI(1):29–42
11. Foote RM, Humphreville JA (1979) Engineering geological approaches to foundations in the karst terrain of the Hershey Valley. *Bull of the Association of Eng Geol* XVI(3):355–381
12. Hardeman WH (1966) *Geologic map of Tennessee*. Tennessee Division of Geology, Department of Environment and Conservation, Nashville
13. Hubbard DA (2003) Use of regional sinkhole mapping for sinkhole susceptibility maps. *ASCE Geotech. Special Publ. No. 122: sinkholes and the engineering and environmental impacts of Karst*. In: Barry B (ed) *Proceedings of the 9th multidisciplinary conference on sinkholes*, Huntsville, 6–10 Sept, pp 61–71
14. Hubbard DA (1984) Sinkhole distribution in the central and northern valley and ridge province, Virginia. In: Barry B (ed) *Proceedings of the 1st multidisciplinary conference on sinkholes*, 15–17 Oct, Orlando, pp 75–78
15. Jennings JE, Brink ABA, Louw A, Gowan GD (1965) Sinkholes and subsidences in the transvaal dolomites of South Africa. *Proceedings of the 6th international conference of soil mechanics*, pp 51–54
16. Kemmerly PR (1981) The need for recognition and implementation of a sinkhole-floodplain hazard designation in urban karst terrains. *Environ Geol* 3:281–292
17. Ketelle RH, Newton JG (1987) Inventory of karst subsidence in the valley and ridge province of east Tennessee. In *Proceedings of 2nd multidisciplinary conference on sinkholes*, Orlando, pp 25–29
18. Mathis H, Wright E, Wilson R (1985) Subsidence of a highway embankment on karst terrain. In *Proceedings of the 36th annual highway geology symposium*, Clarksville, pp 14–27
19. Mellett JS, Maccarillo BJ (1995) A model for sinkhole formation on interstate and limited access highways, with suggestions on remediation. In: Barry B (ed) *Karst Geohazards, engineering and environmental problems in Karst Terrane*. *Proceedings of the 5th multidisciplinary conference on sinkholes*, Gatlinburg, 2–5 Apr, pp 335–339
20. Mills HH, Starnes DD, Burden KD (1982) Predicting sinkhole flooding in Cookeville. *Tenn Tech J* 17:1–20, (Tennessee Technological University), Cookeville, Tennessee
21. Moore HL (1976) Drainage problems in carbonate terrain of East Tennessee. In *Proceedings of 27th annual highway geology symposium*, Orlando, pp 112–131
22. Moore HL (1981) Karst problems along Tennessee highways: an overview. In *Proceedings of the 31st annual highway geology symposium*, Austin, pp 1–28
23. Moore HL (1984) Geotechnical considerations in the location, design, and construction of highways in karst terrain – ‘The Mississippi parkway extension’, Knox-Blount Counties, Tennessee. In *Sinkholes: their geology, engineering, and environmental impact*, *Proceedings of the 1st multidisciplinary conference on sinkholes*, Orlando, pp 385–389
24. Moore HL (1987) Sinkhole development along ‘untreated’ highway ditchlines in East Tennessee. In: Beck B, Wilson W (eds) *Karst hydrogeology: engineering and environmental applications*, *Proceedings of the 2nd multidisciplinary conference on sinkholes*, Orlando, pp 115–119
25. Moore HL (1988) Treatment of karst along Tennessee highways. In: Sitar N (ed) *Geotechnical aspects of karst terrains: exploration, foundation design and performance, and remedial measures*, *ASCE Geotechnical Special Publication No. 14*, pp 133–148
26. Moore HL (1994) *A geologic trip across Tennessee by interstate 40*. University of Tennessee Press, Knoxville, p 339
27. Moore HL (2003) Recent sinkhole occurrences along highways in East Tennessee, a historical perspective. In: *Proceedings of the 54th annual highway geology symposium*, Burlington, 24–26 Sept 2003, pp 46–55
28. Moore HL (2004) Preliminary geotechnical investigation of proposed interchange, I-181 with ext of SR 126, Sullivan, Co., unpublished report files, geotechnical engineering section, TDOT Region One, Knoxville Office
29. Moore HL (2006) A proactive approach to planning and designing highways in East Tennessee karst. *Environ Eng Geosci* XII(2):147–160
30. Moore HL, McDowell L (2008) The development and use of Karst maps in the location of highways in East Tennessee. In: Beck BF (ed) *Sinkholes and the engineering and the environmental impacts of karst*, *Proceedings of the 11th*



- multidisciplinary conference on sinkholes, 22–26 Sept 2008, Tallahassee, ASCE Geotechnical Special Publication No. 183, pp 680–693
31. Myers PB, Perlow M (1984) Development, occurrence, and triggering mechanisms of sinkholes in the carbonate rocks of the Lehigh Valley, eastern Pennsylvania. In: Barry B (ed) Proceedings of the 1st multidisciplinary conference on sinkholes, 15–17 Oct 1984, Orlando, pp 111–115
  32. Mylroie JE (1987) Influence of impermeable beds on the collapse of bedrock voids in the vadose zone. In karst hydrogeology: engineering and environmental applications, Proceedings of the 2nd multidisciplinary conference on sinkholes, Orlando, pp 95–99
  33. Newton JG (1976) Early detection and correction of sinkhole problems in Alabama, with a preliminary evaluation of remote sensing applications. Fed. Hwy. Admin. HPR Report No. 76, Project 930–070., p 83
  34. Newton JG (1981) Induced sinkholes: an engineering problem. J Irrig Drain Div ASCE 107(IR3):175–185, Proc. Paper 16343
  35. Newton JG (1984) Natural and induced sinkhole development, eastern United States: international association of hydrological sciences proceedings, third international symposium on land subsidence, Venice, Italy
  36. Niemiller M (2010) Photo of berry cave salamander. Accessed on 2008 from <http://www.herpetology.us/niemiller/>
  37. Newton JG, Tanner JM (1987) Case histories of induced sinkholes in the Eastern United States. In: karst hydrogeology: engineering and environmental applications, Proceedings of 2nd multidisciplinary conference on sinkholes, Orlando, A.A. Balkema, Netherlands, pp 15–23
  38. Price DJ (1984) Karst progression. In: Barry B (ed) Proceedings of the 1st multidisciplinary conference on Sinkholes, 15–17 Oct 1984, Orlando, pp 17–22
  39. Quinlan JF, Ray JA (1981a) Groundwater basins in the mammoth cave region, Kentucky showing springs, major caves, flow routes, and potentiometric surface. Friends of Karst Occasional Publication, p 2
  40. Quinlan JF, Ewers RO (1981) Hydrogeology of the mammoth cave region, Kentucky: Geological Society of America, Cincinnati field trip no. 8. pp 457–82
  41. Quinlan JF, Ray JA (1981b) Groundwater basins in the mammoth cave region, Kentucky: plate 1 in central Kentucky cave survey bulletin no. 1, Center for Cave and Karst Studies, Western Kentucky University, 1:138,000 map
  42. Quinlan JF, Ray JA (1990) Groundwater remediation may be achievable in some karst aquifers that are contaminated, but it ranges from unlikely to impossible in most: II. Implications for the mammoth cave area of long-term tracer tests and universal, nationwide failure in goal attainment by scientists, consultants, and regulators: In Karst Hydrology\_Proceedings of mammoth cave national park's first annual science conference: U.S. National Park Service, Mammoth Cave National Park, Kentucky, 17–18 Dec 1990, pp 113–14
  43. Reeder PP, Crawford NC (1989) Potential groundwater contamination of an urban karst aquifer - Bowling Green, Kentucky. In: Beck BF (ed) Engineering and environmental impacts of sinkholes and karst, Proceedings of the 3rd multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, Orlando, 2–4 Oct 1989, pp 197–206
  44. Royster DL (1984a) Use of sinkholes for drainage. In: Construction and difficult geology: karstic limestone, permafrost, wetlands, and peat deposits; Trans. research board record 978, Washington DC., pp 18–25
  45. Royster DL (1984b) Unpublished drawing of cap grouting on I-24, Montgomery Co., Tennessee. In: Geotechnical engineering section files, Tennessee Dept. Transp., Nashville
  46. Sowers G (1976) Foundations bearing in weathered rock. Proceedings speciality conference on rockeng. for foundations and slopes 2, Univ. of Colorado, 15–18 Aug 1976
  47. Sowers GF (1984) Correction and protection in limestone terrain. In: Beck B (ed) Sinkholes: their geology, engineering and environmental impact, Proceedings of the 1st multidisciplinary conference on sinkholes, Orlando, pp 373–378
  48. Stephenson JB, Beck B (1995) Management of the discharge quality of highway runoff in karst areas to control impacts to groundwater – A review of relevant literature. In: Beck BF (ed) Karst geohazards – engineering and environmental problems in karst terrane, Proceeding of the fifth multidisciplinary conference on sinkholes and the engineering and environmental impacts of Karst, Gatlinburg, 2–5 Apr 1995, pp 297–321
  49. Stephenson JB, Zhou WF, Beck B, Green T (1997) Management of highway storm water runoff in karst areas – baseline monitoring and design of a treatment system for a sinkhole at the I-40/I-640 interchange in eastern Knoxville, Tennessee. In Proceedings of the 48th annual highway geology symposium, Knoxville, 8–10 May 1997, pp 24–34
  50. Vance SJ (2003) Perceived risk versus cost in Karst remediation: a case history. In: Beck B (ed) Sinkholes and the engineering and environmental impacts of karst, Proceedings of the 9th multidisciplinary conference on sinkholes, ASCE Geotechnical Special Publication No. 122, pp 652–658
  51. Veni G (1987) Fracture permeability: implications on cave and sinkhole development and their environmental assessments. In karst hydrogeology: engineering and environmental applications, Proceedings of the 2nd multidisciplinary conference on sinkholes, Orlando, pp 101–105
  52. White WB, White EL (1987) Ordered and stochastic arrangements within regional sinkhole populations. In: karst hydrogeology: engineering and environmental applications, Proceedings of the 2nd multidisciplinary conference on sinkholes, Orlando, pp 85–90

